Reprinted from Wildlife Society Bulletin
Volume 28, Number 4, Winter 2000

Mapping forest canopy gaps using air-photo interpretation and ground surveys

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Abstract Canopy gaps are important structural components of forested habitats for many wildlife species. Recent improvements in the spatial accuracy of geographic information system tools facilitate accurate mapping of small canopy features such as gaps. We compared canopy-gap maps generated using ground survey methods with those derived from air-photo interpretation. We found that maps created from high-resolution air photos were more accurate than those created from ground surveys. Errors of omission were 25.6% for the ground-survey method and 4.7% for the air-photo method. One variable of interest in songbird research is the distance from nests to gap edges. Distances from real and simulated nests to gap edges were longer using the ground-survey maps versus the air-photo maps, indicating that gap omission could potentially bias the assessment of spatial relationships. If research or management goals require location and size of canopy gaps and specific information about vegetation structure, we recommend a 2-fold approach. First, canopy gaps can be located and the perimeters defined using 1:15,000-scale or larger aerial photographs and the methods we describe. Mapped gaps can then be field-surveyed to obtain detailed vegetation data.

Key words air photo, canopy, forest, gap, ground survey, map, remote sensing, wildlife habitat

Wildlife managers are interested in forest canopy gaps because gaps create or alter wildlife habitat and because some processes of gap creation can be managed, for example, timber harvest. Canopy gaps, defined as openings in the tree canopy of a forest, can range from <25 m^2 to about 0.1 ha; large-scale blowdowns can range from one to 3,000 ha (Lorimer 1989). In this paper we focus on small-scale gaps (100–2,500 m^2).

Forest canopy gaps have been studied intensively by ecologists (Lawton and Putz 1988). Gaps are created by a variety of factors, including treefalls, tree disease, silvicultural practices, and wildlife management practices (Runkle 1989, Suarez et al. 1997). The dynamics of gap creation and closure have important implications for tree regeneration and recruitment (Runkle and Yetter 1987; Runkle 1989, 1998). Canopy gaps change the physical and biological attributes of the forest. More light reaches the forest floor, allowing recruitment of shade-intolerant grasses, forbs, shrubs, and trees (Poulson and Platt 1989). By controlling competition for light, gaps also greatly influence radial growth of trees (Lorimer and Frelich 1989, Nowacki and Abrams 1997). All of these changes cumulatively result in a habitat quite different in composition and structure from a closed-canopy forest.

Wildlife professionals need accurate maps of gap size and location to assess spatial relationships between wildlife species and forest canopy gaps. The spatial properties of the forest are sometimes critical attributes of wildlife habitat. At the stand scale, diversity of bird communities tends to rise as number of canopy gaps increases (Derleth et al.

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1989, Lent and Capen 1995), but too much forest fragmentation can affect reproduction rates of interior forest-nesting birds at the stand and regional scales (Robinson et al. 1995, Fenske-Crawford and Niemi 1997, Temple and Flaspohler 1998). Edge quality can influence bird nest-predation rates. For example, Suarez et al. (1997) found that nest-predation rates were nearly twice as great along agricultural and other abrupt edges than along edges where plant succession was allowed to progress. Differences in predator activity or nest visibility are believed to account for most of the observed differences among edge types. For some species there is evidence that habitat changes extend some distance from the gap edge into the forest. Demaynadier and Hunter (1998) found that edge effects extended 25–35 m from the gap edge into the forest for some amphibian species. Canopy-gap information may be useful for refining habitat associations for a wide range of forest-dwelling wildlife species, including songbirds (Hunt 1996, Kilgo et al. 1996, Smith and Dallman 1996), gamebirds (Gustafson et al. 1994), bats (Wunder and Carey 1996), amphibians (Demaynadier and Hunter 1998), and small mammals (Sekgororoane and Dilworth 1995).

Land managers can manipulate the location and size of canopy gaps through silvicultural practices. Harvest practices such as clear-cutting, for example, can precipitate major changes in bird species composition (Annand and Thompson 1997, Thiollay 1997). But harvest practices can be modified to mimic naturally occurring gap dynamics, thus maintaining the environmental conditions required by native plants and animals (Chambers et al. 1999).

Geographic information system (GIS) maps created from remotely sensed data, such as air photos and satellite imagery, are commonly used to characterize major habitat cover types (Scott et al. 1993). Recent improvements in the spatial accuracy of Global Positioning System (GPS) receivers and GIS tools now facilitate accurate mapping of small habitat features like forest canopy gaps. Various methods of canopy-gap measurement have been described, including airborne spectrographic imaging and digital elevation models (Blackburn and Milton 1996, Tanaka and Nakashizuka 1997). In addition, computer models are available to simulate forest-gap dynamics (Lindner et al. 1997) and also could potentially model changes in forest wildlife habitat. However, advanced gap-delineation methods require collection and analysis of specialized remote sensing data, which is beyond the resources of most wildlife management agencies.

The purpose of this study was to compare canopy-gap maps generated using ground-survey methods versus aerial photo interpretation for a floodplain forest plot. We assessed the utility of the 2 methods to generate gap maps for wildlife habitat management or research studies. Our ultimate goal for mapping canopy gaps was to examine the spatial relationships between canopy gaps and songbird nest placement. In addition to the gap data, we collected songbird nesting data that will be used to test hypotheses about how nest success varies based on proximity to gaps.

Methods

The study area was a 15.4-ha plot of floodplain forest located at the mouth of the Root River flowing into the Upper Mississippi River, Houston County, Minnesota (Latitude 43.760°, Longitude -91.258°). The study area was part of the Driftless Area ecoregion (Bailey's Section 222L, McNab and Avers 1994). Geologically, the area was characterized by broad, steep-sided bedrock ridges, bisected by the Mississippi River floodplain. Elevations ranged from 200 to 400 m, precipitation averaged 740–890 mm annually, and average annual temperature was 7–10°C (McNab and Avers 1994). In the study area, the overstory was dominated by mature silver maple (*Acer saccharinum*), with an understory of young green ash (*Fraxinus pennsylvanica*) and a minor component of swamp white oak (*Quercus bicolor*). Mean tree diameter at breast height of floodplain forests in the study area was approximately 35 cm, with a mean basal area/tree of 0.093 m^2 (Knutson and Klaas 1998). Flood recurrence interval for this stand was approximately 5 years. Canopy gaps in the study area resulted primarily from the death of old trees, particularly large American elm (*Ulmus americana*) trees that died during the last decade, and a few blowdowns. No timber harvest had occurred for about 70 years. Canopy gaps were dominated by reed canary grass (*Phalaris arundinaceae*) and riverbank grape (*Vitis riparia*), with a minor component of shrubs and saplings. Tree regeneration in the gaps was retarded by dense grass and forb cover that outcompeted tree seedlings (Knutson and Klaas 1998).

The study area also was part of the United States Fish and Wildlife Service's (USFWS) Upper Mississippi River National Wildlife and Fish Refuge, a globally important bird area (United States Department of the Interior 1998); therefore, birds were a focus of management (Knutson et al. 1996, Knutson and Klaas 1997). Detailed descriptions of floodplain forests in the study area and a discussion of management issues can be found in Knutson et al. (1996), Knutson and Klaas (1998), and Knutson et al. (2000).

Gaps derived from ground-survey data

We conducted the ground survey during July and August 1997. Field workers systematically surveyed the plot along 25-m-wide transects, recording all canopy gaps >10 m across (shortest dimension, minimum size = 0.01 ha or 100 m^2). We defined gaps as areas with a >5-m difference in height between canopy trees surrounding the gap and vegetation within the gap, visually estimated by field workers. We recorded gap size by measuring the maximum length and its compass orientation and measuring the maximum width, perpendicular to the length. We recorded the shape of each gap with a pencil sketch. We recorded the approximate locations of gap centers using a Rockwell Precision Lightweight GPS Receiver v.96® (Rockwell International, Costa Mesa, Calif.). Because the spatial resolution of the GPS receiver was approximately 9 m, we did not use it to define gap perimeters. We divided the gaps into 4 quarters of approximately equal area and recorded the following vegetation characteristics: percentage cover of grasses, forbs, bare ground, shrubs, and all vegetation, and numbers of trees and snags.

We created maps of gaps generated from ground-survey data using a GIS (Arc Info v. 7.1.2®, ESRI, Redlands, Calif.). We generated a point coverage of gap centers and linked it with the length, width, and vegetation measurements. From these, we generated oval polygons around each gap center, corresponding to gap sizes. (The pencil sketches proved to be subjective and not suitable for transfer into a GIS coverage.) We summarized the vegetation measurements for all gaps identified by the ground survey.

Gaps derived from interpretation of air photos

We used color-infrared air photos (1:15,000 scale, 28 August 1997) to generate a second, independent map of canopy gaps. Each photograph was scanned at high resolution to create an 8-bit grayscale, 800 pixels/inch (ppi), hardware-derived image of the plot. The nominal scale of the scanned image was 1:15,380. At 800 ppi, each pixel of the scanned image represented approximately 0.24 m^2 on the ground.

To precisely locate (rectify) the air photos, we collected 8 ground control points (GCPs), 150–717 m outside the plot boundary, using a Trimble GeoExplorer® GPS receiver. We set the receiver's operating parameters in accordance with the base station and collected the GCPs using the receiver's high-accuracy mode (error = ±1 m). Each GCP is an average of >150 differentially corrected points recorded at that position. We post-process differentially corrected the GCPs with Trimble's Phase Processor v.1.0® software (Trimble Navigation Limited, Sunnyvale, Calif.). We rectified the scanned air photo with the differentially corrected GCPs using affine transformation algorithms mediated by ERDAS Imagine® software (ERDAS, Atlanta, Ga.). We used an affine rectification because the plot had little topographic relief.

We recorded all gaps identifiable from the stereo air photos using a Topcon Model 3® Mirror Stereoscope (Topcon America Corporation, Paramus, N. J.). The 3-dimensional image was necessary to accurately identify gaps (Figure 1). We marked the gaps on a Mylar overlay; then we digitized the gaps directly into the computer using an on-screen rectified image of the same photograph and the Mylar overlay as a reference. We eliminated gaps that were <10 m in diameter.

Comparison of ground-survey and air-photo methods

We estimated errors of commission and omission for the canopy-gap maps by field reconnaissance

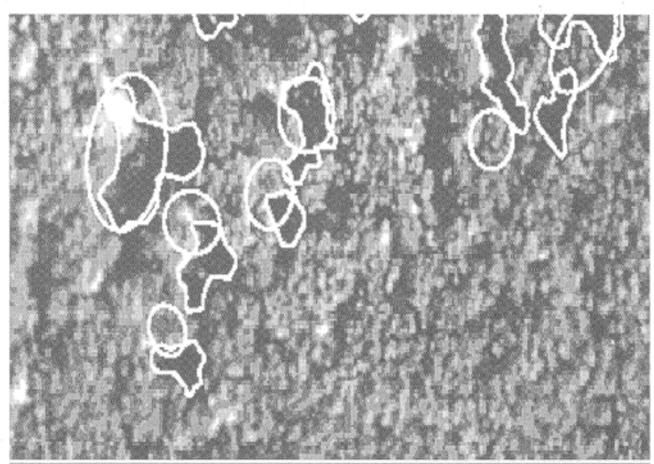


Figure 1. An example of canopy gaps in a floodplain forest plot identified by air-photo interpretation (irregular shaded polygons) and ground survey (ovals) with a rectified air photo as background. The rectified image was viewed using a 3-dimensional stereoscope to accurately identify canopy gaps.

(ground truth visit). After leaf-off, we relocated each gap identified by either method on the ground using a GPS receiver and a reference air photo. We calculated errors of commission by counting the number of gaps that were erroneously identified by either method—that is, did not actually exist on the ground or did not meet the criteria, in the case of the ground-survey gaps. We calculated errors of omission by mapping all verified gaps and counting gaps that were missed by either method. We assumed that we identified all canopy gaps ≥10 m in diameter using a combination of both methods and field reconnaissance.

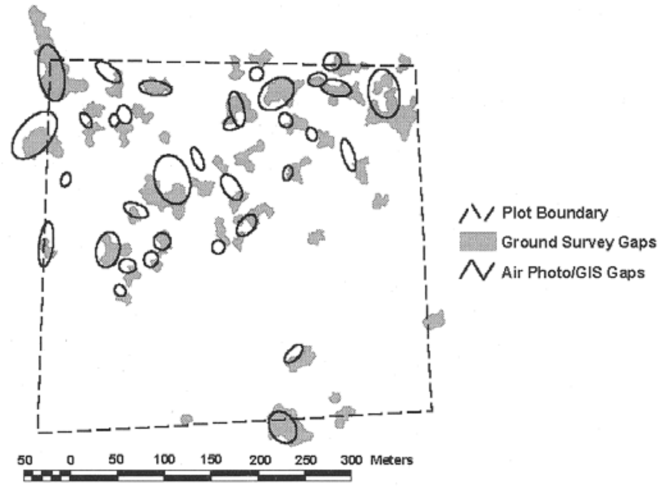


Figure 2. Canopy gaps in a floodplain forest plot identified by air-photo interpretation (irregular shaded polygons) and ground survey (ovals).

Distances from nests to canopy-gap edges

We wanted to assess whether the methods used to generate canopy-gap maps can influence assessment of spatial relationships between gaps and wildlife observations. We measured distances between songbird nest locations, recorded with the Rockwell GPS receiver in 1996 and 1997, and the nearest gap edge, as defined by each gap mapping method. We removed errors of commission (erroneous gaps) for each method before the analysis. Because songbird nest locations also have associated error (GPS receiver error is about 9 m), we also generated 100 random points within the plot as a simulation of random nest locations and conducted a similar analysis. We used ArcView® (ESRI, Redlands, Calif.) software (scripted in Avenue®) to measure the distance from nests and simulated nests to the gap edge. A Student's *t*-test was used to compare mean distance from nests to ground-survey gap edges versus air-photo-derived gap edges.

GIS accuracy assessment

We recorded 5 checkpoints to compare the positional accuracy of the rectified image and the Rockwell PLGR+96 GPS receivers used by the ground crew to record gap centers. Checkpoints were landmarks clearly apparent on the ground and on the aerial photos, such as highway intersections. We calculated the distance between checkpoints recorded by the GPS receiver and corresponding points obtained from the rectified image. We estimated accuracy of the GCPs, the Rockwell PLGR+96 GPS units, and calculated root mean squared (RMS) errors for all map products.

Results

Gaps averaged 422 m^2 (ground survey) and 446 m^2 (air photos) in size, with a range of 100 to 2,242 m^2. Total vegetative cover in the surveyed gaps was great (>90%), with forbs providing >50% and shrubs approximately 20% of the vegetative cover. Our final field reconnaissance revealed 43 canopy gaps in the study area (Figure 2). We delineated 34 gaps by the ground-survey method, of which 2 were not valid (5.9% commission rate) and 11 were missed (25.6% omission rate). In the aerial-photo method, we delineated 45 gaps, of which 4 were not valid (8.9% commission rate) and 2 were missed (4.7% omission rate).

Distances between real nest locations and the nearest canopy gap calculated from the ground survey ($\bar{x}$=17.1 m, SE=4.1 m, n=52) were longer than the distances calculated using air photos ($\bar{x}$=13.3 m, SE=2.9 m, n=52; t_{51}=1.78, P<0.08; Table 1). Distances between the simulated random nest locations and the nearest canopy gap calculated from the ground survey ($\bar{x}$=44.7 m, SE=4.0 m, n=100) were nearly twice the length calculated using air photos ($\bar{x}$=28.5 m, SE=2.6 m, n=100; t_{99}=6.48, P< 0.001).

The distance from the GCP locations to the base station was <14.8 km. The expected accuracy of the differentially corrected GCPs ranged from 0.3 to 1.0 m of error. The process of rectifying the image with the above GCP locations yielded an RMS error of 0.3 m (ground units). This is the error of the reference grid that provides real-world positions for each pixel of the scanned image. The mean distance between checkpoints collected by a Rockwell PLGR+96 GPS receiver and image locations from the rectified aerial image was 2.1 m (range=0.9–3.0 m). The mean error estimate by the PLGR+96 receiver was 8.6 m (range=8.3–8.9 m).

Table 1. Mean distance (m) from songbird nests to the nearest canopy-gap edge, calculated from air-photo-derived gaps and ground-surveyed gaps in a floodplain forest plot during 1997.

Species	*n*	Air Photo Mean dist. (m)	Air Photo SE	Ground Mean dist. (m)	Ground SE
American redstart (*Setophaga ruticilla*)	25	13.5	9.8	18.2	18.0
American robin (*Turdus migratorius*)	5	21.2	16.3	30.6	15.7
Black-capped chickadee (*Poecile atricapillus*)	1	6.8	0.0	5.0	0.0
Blue-gray gnatcatcher (*Polioptila caerulea*)	1	16.8	0.0	25.7	0.0
Brown creeper (*Certhia americana*)	1	5.7	0.0	17.5	0.0
Eastern wood-pewee (*Contopus virens*)	2	55.6	22.2	47.9	30.9
Great-crested flycatcher *Myiarchus crinitis*)	2	4.3	1.5	1.8	0.0
Gray catbird (*Dumetella carolinensis*)	7	4.6	2.3	6.6	0.9
Northern cardinal (*Cardinalis cardinalis*)	1	0.2	0.0	1.8	0.0
Rose-breasted grosbeak (*Pheucticus ludovicianus*)	1	11.5	0.0	18.9	0.0
Yellow warbler (*Dendroica petechia*)	6	9.4	7.2	11.3	6.8
All species	52	13.3	2.9	17.1	4.1

Discussion

For purposes of accurately recording number, location, and shape of canopy gaps, air photos were superior to ground surveys in our study. Our finding that distances from gap edges to nests were greater using the ground-survey method is consistent with the observed gap omission rate for the ground survey. It also demonstrates that missing a large number of gaps could bias a spatial analysis of the nest data, obscuring potential associations between nests and gaps.

Several problems may have affected the accuracy of our ground data. The high gap omission rate of ground data resulted from logistical difficulties in systematically locating and measuring canopy gaps on the ground. Estimating a 5-m height difference between canopy trees surrounding the gap and vegetation within the gap (determining what is a gap and what isn't) proved more difficult for field observers than expected. We recorded gap locations with the GPS at the approximate center of the gap. Instead, we should have recorded gap locations at the intersection of the maximum length and the maximum width axes to create the most accurate GIS representations of the gaps. In contrast, in the air-photo method we recorded the actual perimeter of the gap, rather than a generalized oval. Precise perimeter locations may be important if edge effects are of interest. Also in the aerial-photo method we were limited only by the gap size we could perceive on the image, which provides the option of examining size threshold effects on response variables. In the ground survey, size criteria must be determined before beginning field data collection. In practice, we found that 7–10 m was the minimum diameter gap we could identify from the air photos.

The major advantage of ground surveys is that they provide specific information on vegetation characteristics within the gap, such as cover estimates, and counts of trees and shrubs. The air photos do not allow collection of that level of detail. A 10-m gap on a 1:15,000-scale air photo is represented by only 0.67 mm on the print, too small to allow identification of the vegetative composition of the gap's interior. Also, some applications require that gap perimeters be defined by tree boles (Runkle 1998); this information is best obtained by ground surveys.

Cost-effectiveness is a critical factor in choosing a useful method of mapping canopy gaps. Air-photo-derived gap maps have a distinct advantage in terms of labor. Approximately 11 person-days were needed to ground-survey the study area and convert these data into a GIS coverage. The aerial-photo method required 4 person-days to collect ground control points, digitize, and convert the data into a GIS coverage.

Despite major technological advances in GPS instruments and GIS software, some practical limitations remain. Interference with the satellite's timing signals (multipath) may affect the positional accuracy of the PLGR+96 GPS receivers (Wilie 1989). Tree leaves are a significant source of

Canopy gaps may be important to a wide range of forest-dwelling wildlife species, including songbirds, gamebirds, bats, and small mammals. Land managers can manipulate the location and size of canopy gaps through silvicultural practices. Photo by Melinda Knutson.

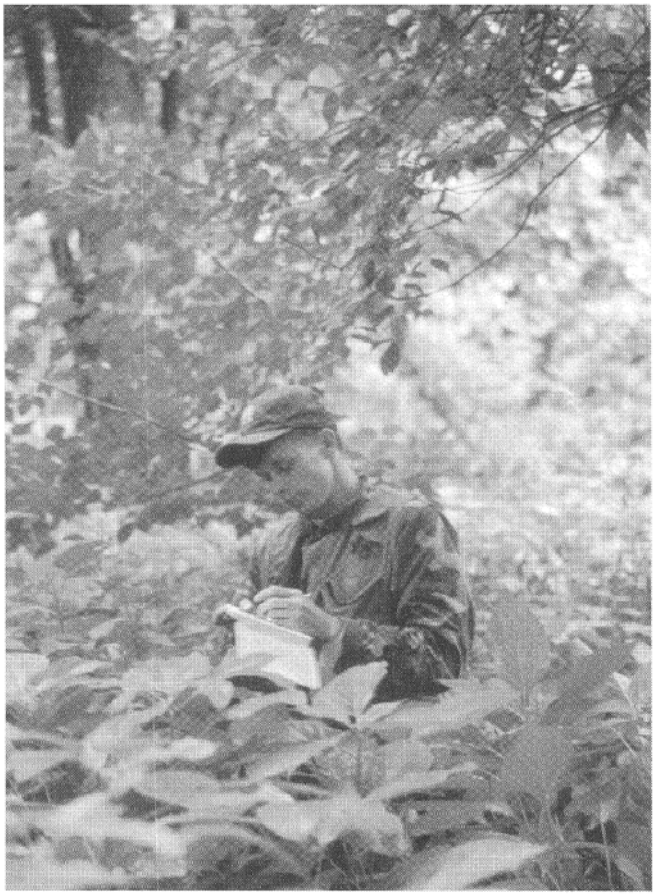
multipath for GPS satellite signals in forest habitats. Displacement between our checkpoints and image points, as well as shifted positions of individual gaps between the data sets, suggests multipath may have affected location data collected on the ground. Solutions to this problem include taking GPS locations after leaf-off or raising a receiver antenna above the canopy. We recommend considering options to reduce multipath problems when working in forests. In the case of nest locations, there are practical difficulties associated with marking nest locations during the summer breeding season and recording these locations with a GPS after leaf-off, some of which include marker losses, failing to find all markers, and field staff turnover. In addition, canopy heights exceeded 20 m in our study area, which complicates raising an antenna above the canopy.

The scanned and rectified image was not influenced significantly by multipath, because the GCPs used to rectify the image were collected after leaf-off. Canopy-gap delineation in areas with much topographic relief may require more GCPs and a higher-order rectification algorithm than we used working on relatively level ground. Visual interpretation of forest canopy gaps in areas with rugged topography also may be challenging because a gap located on a steep slope is more difficult to identify and delineate. Other methods of rectifying photos for locations with steep terrain are available (Reutebuch and Shea 1988).

If research or management goals require positional accuracy of canopy gaps and specific information about vegetation structure, we recommend a 2-fold approach. First, canopy gaps can be located and the perimeters defined using 1:15,000-scale or larger air photos and the methods described in this paper. Next, ground surveys of gaps can be used to obtain more detailed vegetation measurements. This approach has the additional benefit of adding efficiency to the field component of the work (workers can navigate to gaps using a GPS receiver). If the goal is to obtain general information about gap vegetation composition and structure, it is most efficient to sample the gaps rather than conduct a complete survey. The air-photo map of gaps provides a "population" of gaps from which to select a sample. If the study requires only gap location and size, then the air-photo method is efficient and accurate. For example, assessing the spatial relationships between bird nests and canopy gaps requires accurate spatial locations of nests and gaps, but may not require detailed vegetation information about the gap itself. We need additional research at other study sites to determine whether air-photo methods are generally more efficient and accurate than ground surveys for creating GIS canopy-gap maps. We did not use multiple study sites because we were focused on methods development.

For large forest areas (>100 ha), we propose that remote sensing methods will prove most efficient to map canopy gaps. Ground surveys at this scale are prohibitively costly and time-consuming. Forestry professionals have experimented with mapping forest canopy gaps using advanced remote sensing methods; these should be considered if very large areas are targeted and cost is not a barrier. Blackburn and Milton (1996) used a

The study area was a large tract of floodplain forest located near the mouth of the Root River flowing into the Upper Mississippi River in Houston County, Minnesota. Bluff lands and dissected plateaus characteristic of the Driftless Area Ecoregion surround the study area. Photo courtesy of the United States Fish and Wildlife Service.



Ground surveyors recorded the location of the gap center, as well as the percentage cover of grasses, forbs, bare ground, and shrubs and numbers of trees and snags. Ground surveys were also used to obtain ground control points to rectify aerial photos and verify gaps identified by aerial-photo interpretation. Photo by Carl Korschgen.

Compact Airborne Spectrographic Imager (CASI) to monitor gap formation, canopy regeneration, and spatial arrangement of gaps. A CASI produces high-resolution multi-spectral images of the forest canopy. This method provides the added advantage of increased spectral resolution. Another approach to delineate canopy gaps from remotely sensed data was applied by Tanaka and Nakashizuka (1997) in the Ogwa Forest Reserve of central Japan. They used a Digital Elevation Model (DEM) of the ground surface and a DEM of the forest's canopy surface to detect and monitor canopy gaps. This method provided a 3-dimensional model of the forest canopy and allowed them to monitor the regeneration of the forest canopy. The technology required for both of these methods is costly at present and is likely beyond the resources of most wildlife agencies. Our methods rely on resources available to most natural resource management agencies: 1:15,000 air photos and computers with GIS programs.

Acknowledgments. This project was supported by the United States Geological Survey, Upper Midwest Environmental Sciences Center; the United States Fish and Wildlife Service, Region 3 Nongame Bird Program; and the Resource Analysis Department and Resource Studies Center, St. Mary's University of Minnesota. The paper was greatly improved through constructive review by G. Nowacki and 2 anonymous reviewers. We thank C. K. Korschgen, L. R. Robinson, W. J. Klouda, D. McConville, J. Nosek, X. Yang, D. Mierau, R. Vose, C. M. Sveum, J. E. Lyon, J. Ruhser, T. Hoffman, and H. DeHaan for their assistance. Identification of commercial equipment and software in the text does not imply endorsement by the United States government.

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Associate editor: *Smith*